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A NEUTRON MONITOR FOR SIMULTANEOUS MEASUREMENT OF FLUENCE AND DOSE EQUIVALENT

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Industrial Hygiene and Safety Division

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ABSTRACT

A neutron detector which has application as both an area monitoring instrument and a criticality dosimeter is under development at Argonne National Laboratory. The detector simultaneously measures both dose equivalent and fluence from an exposure to fast neutrons.

The moderator consists of a 12-in.-diameter, aluminum-encased paraffin sphere. The neutron sensors are nine thermal activation foils located within the moderator. The neutron fluence is determined by activation of six foils symmetrically located one inch below the surface of the moderator. For this foil array, the summed activity is nondirectional and proportional to the fluence within 10 percent over the investigated energy range from 20 keV to 2.3 MeV. The neutron dose equivalent is determined from activation of three symmetrically interlocked foils at the center of the moderator, and the summed activity is proportional to the dose equivalent within 75 percent over the same energy range.

A response correction technique is described which, for monoenergetic neutrons, brings the dose equivalent to within about 10 percent. The average sensitivity of the monitor over the stated energy range, using indium foils, is 76 cpm per mrem/hr and 25 cpm per n/cm^2-sec at the end of one half-life exposure at uniform radiation level.

INTRODUCTION

An examination of the neutron thermalization characteristics of a spherical hydrogenous moderator has disclosed several relationships amenable to exploitation in the design of a simple yet versatile neutron detector. Some of these relationships are new and some have been explored by others.

Pertinent considerations leading to the design concept for the instrument include the following:

1. The thermal-flux-density distribution in a hydrogenous moderator has been studied by a number of investigators under various moderator-sensor geometries.[1-6] In all cases, a similar distribution was seen. Characteristically, if the moderator is sufficiently large, the thermal flux density increases from some nominal value at the front surface of the moderator to a maximum at an energy-dependent depth; thereafter, it decreases with depth to the rear surface. Calculations of our own, utilizing multigroup diffusion theory, show the same characteristics for spherical detectors. In addition, these calculations indicate that the response of a 12-in.-diameter sphere having a symmetrical array of sensors located about one inch below the surface is fairly independent of incident neutron energy. (These calculations are currently being revised to improve accuracy and are not considered further in this report.)

2. Several investigators[7,8] have shown that a polyethylene sphere of about 10-in. diameter having a small sensor at the center exhibits a variation of sensitivity with incident neutron energy approximating the currently accepted variation of dose equivalent with neutron energy. Our work indicates that the same result can be achieved for a 12-in. sphere and a 2-in. sensor.

3. A spherical moderator with a central sensor is inherently nondirectional. The same moderator having a large number of symmetrically distributed noncentral sensors with a summed response also is inherently nondirectional.

4. If measurements are made in a neutron radiation field utilizing two detectors having substantially different energy responses, one can determine an effective neutron energy for this field. It is easy to postulate energy spectra for which this effective energy would be quite misleading. If used cautiously, however, it can have direct value in biological irradiation experiments,[4] and many radiation protection situations.[2] One also may utilize the effective neutron energy to determine a suitable sensitivity correction for a detector with a nonideal response curve.

5. The use of a neutron moderator with thermal sensors affords the instrument designer a valuable flexibility. One can select the sensor according to the type of source and the information desired. Active sensors such as GM tubes wrapped in silver foil may be used for pulsed sources, and boron trifluoride or lithium iodide counters for continuous emission sources. Passive sensors, such as foils of indium, dysprosium, cobalt, and gold, may be used with any source and for work involving a wide range of integration times.

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DETECTOR

A sketch of the geometry chosen for the sensors is shown in Fig. 1. Since the type of sensor is in principle unimportant, passive foils are shown for simplicity. The dosimetric array is a symmetrical group of three sensors at the center of the moderator. The flat-response array consists of six sensors equidistant from the center and lying on the rectangular coordinate axis.

Figure 2 shows the passive foil detector as finally fabricated. It consists of two 12-in.-diameter, hemispherical aluminum shells which have been filled with paraffin moderating material. On each of the three coordinate axes, Lucite holders and plugs provide externally accessible positions for the six 2-in.-diameter thermal activation foils comprising the flat-response array. The foils are located one inch below the surface of the moderator and 5 in. from the center.

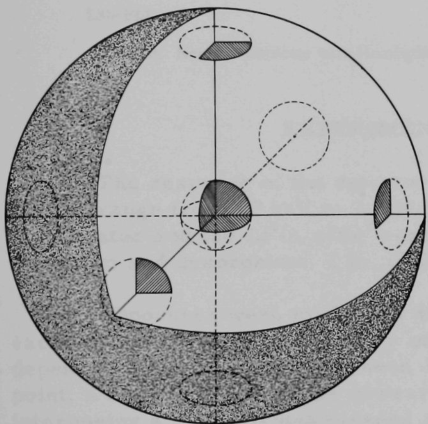

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Fig. 1. Sensor Geometry for Spherical Foil Neutron Detector

235-916

Fig. 2. Neutron Detector Fully Assembled and Ready for Use

Figure 3 shows the same detector with the hemispheres separated for access to the central dosimetric array. A slotted Lucite cylinder is used to hold three foils symmetrically interlocked in such a manner that there is one foil in each of the three rectangular coordinate planes of the sphere.

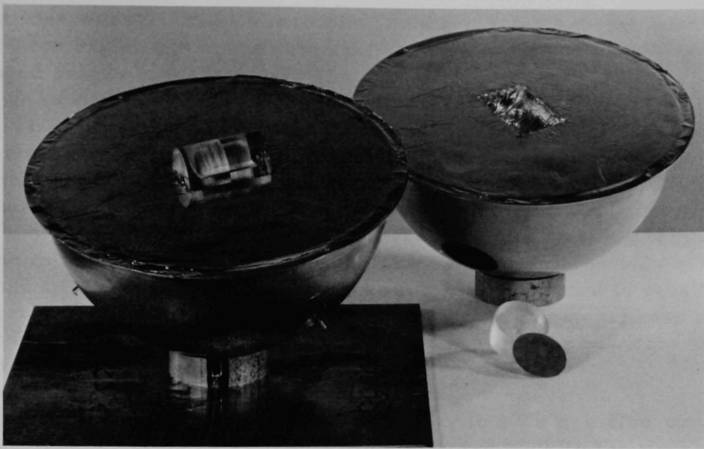

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Fig. 3. Neutron Detector with Hemispheres Separated for Access to Central Array

EXPERIMENTAL RESULTS

The response of the detector was determined experimentally in the energy range from 20 keV to 2.3 MeV through use of a Van de Graaff proton accelerator and the $Li^7(p, n)Be^7$ reaction. The thermal activation foils were of indium and dysprosium, 2 in. in diameter and 10 mils thick.

Exposures were made at a distance of 105 cm from the target, and each exposure was approximately one hour in duration. The energy-dependent fluences ranged between 300 and 2,000 n/cm^2-sec. At each energy point, a determination of the scattered-neutron background was made by interposing a $16\frac{1}{4}$-in.-long tapered shadow cone between the target and source, and exposing for the same length of time at a comparable neutron fluence. Correction factors for background ranged between 6 and 14 percent of the total (cone removed) activity. For energies of 70 keV and above, exposures were made at 0° to the direction of the proton beam. At lower energies, it was necessary to expose at an angle of 60° to the direction of the proton beam to achieve the desired energy stability.

The neutron flux was measured with a Precision Long Counter built in accordance with the DePangher design developed at Hanford.[9] Earlier experiments indicated that use of the conventional ±60° experimental arrangement (with the Long Counter monitoring the beam at -60° during detector exposure at +60°) resulted in a prohibitive background due to scattering off the Long Counter and 0° beam scatter from environmental materials.

275-734

Fig. 3. Neutron Dosimeter with [illegible] Chamber Assy

EXPERIMENTAL RESULTS

The response of the detector was determined experimentally in the energy range from 20 keV to 1.3 MeV through use of a Van de Graaff proton accelerator and the $Li^7(p,n)Be^7$ reaction. The thermal activation foils were of indium and dysprosium, 2 in. in diameter and 10 mils thick.

Exposures were made at a distance of 10 cm from the target and each exposure was approximately one hour in duration. The energy-dependent fluences ranged between 100 and 3,000 n/cm^2 sec. At each energy point, a determination of the scattered-neutron background was made by interposing a 16-in.-long tapered shadow cone between the target and source, and exposing for the same length of time at a comparable neutron fluence. Correction factors for background ranged between 6 and 14 percent of the total (cone removed) activity. For energies of 70 keV and above, exposures were made at 0° to the direction of the proton beam. At lower energies, it was necessary to expose at an angle of 60° to the direction of the proton beam to achieve the desired energy stability.

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Calibrations were, therefore, achieved by alternating between Long Counter the detector exposures at the same physical position and normalizing with integrated proton beam current.

To study the extent of variation in sensitivity due to rotational orientation of the detector with respect to the incident neutron beam, at least two orientations were tried at each energy. Figure 1 shows that there are two geometrically extreme cases of incidence. The first is that in which a radial line between the source and the detector center passes through a sensor, and is referred to as "head-on." The second is where all sensors are equidistant from this line (and its backward extension) and is referred to as "trisection." A third, intermediate case exists when two sensors are equidistant from this line and lie in a common plane; this is referred to as a "bisection."

Each foil was counted for beta activity in a 2π gas-flow proportional counter. The counting rates then were corrected back to the time at which the exposure ended, normalized to an exposure time of one half-life for the isotope of interest (54.2 min for indium-116m; 139.2 min for dysprosium-165), and also normalized to a neutron fluence of 1 n/cm^2-sec.

The results for the more comprehensively exposed indium foils are shown in Fig. 4. The most significiant information in this plot is the nature and magnitude of the directional effect. For the outside array, any directional difference is masked by statistical spread in the points; variations due to direction of incidence appear to be not greater than ±5 percent. A different and unexpected situation occurs for the center array: a directional effect of about ±10 percent is seen. Since the head-on orientation showed highest sensitivity, it is believed that the low hydrogen density (compared to paraffin) of the Lucite foil cylinders may be responsible.

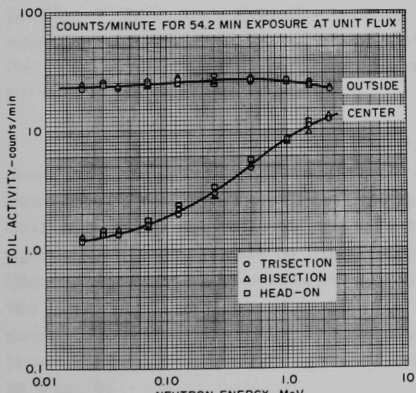

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Fig. 4. Summed Foil-array Activity as Experimentally Determined, Showing Sensitivity Variation with Neutron Energy and Detector Orientation

Although the data are not presented here, the individual activity of each of the six outer foils varied greatly. It was possible to define not only the primary neutron beam direction, but also the general direction of scattered neutron sources by inspection of the activation data.

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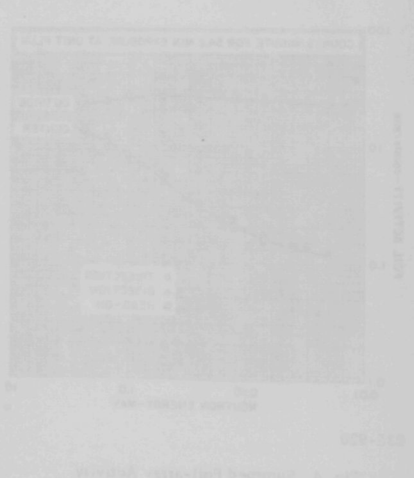

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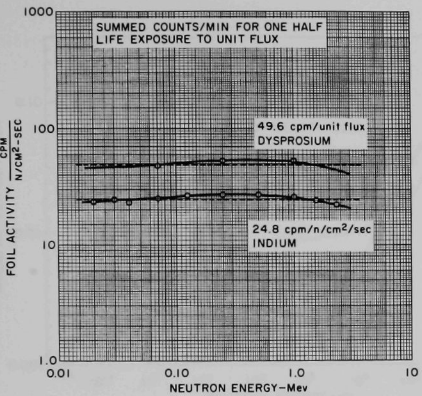
Figure 5 shows the response of the outer foil array, obtained from indium and dysprosium data averaged over the three incidence orientations.



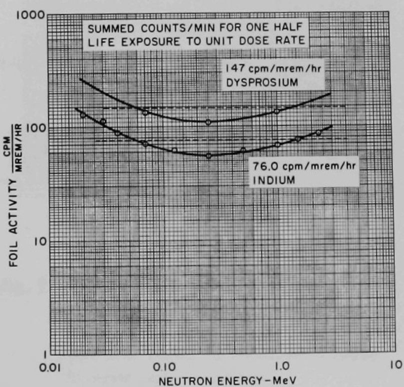
235-921

Fig. 5. Summed Outer Foil-array Activity, Showing Sensitivity Variation with Energy and Foil Material

In the energy range tested, the 1/E-averaged indium sensitivity was 24.8 cpm for a unit fluence irradiation, and the 1/E-averaged dysprosium sensitivity 49.6 cpm. In general, the "flatness" was about 10 percent in the tested energy interval, and it appears that the sensitivity will decrease at both lower and higher energies.

Figure 6 shows the response of the inner foil array, again obtained from incidence-average indium and dysprosium data. Over the same energy range, the indium sensitivity ranged between 56 and 132 for a 1/E-averaged sensitivity of 76.0 cpm per mrem/hr, while the dysprosium ranged between 110 and 260 for a 1/E average of 147 cpm per mrem/hr. A comparison of the curves obtained in this work with dosimetric data of Bramblett et al.,[7] and Hankins,[8] as shown in Fig. 7, indicates that the indium sensitivity will rise with decreasing energies to a maximum of about 260 cpm per mrem/hr, and thereafter will decrease to about 100 cpm per mrem/hr in the epithermal region.

Since the outer sensor array does not have an absolutely flat response and the inner array has only a crude approximation to dosimetric response, it is desirable to make use of the self-correcting feature inherent in the detector. A plot of the ratio of outer array activity to inner array activity as a function of energy is shown in Fig. 8.



235-922

Fig. 6. Summed Inner Foil-array Activity, Showing Sensitivity Variation with Energy and Foil Material

To determine fluence and dose equivalent accurately, it is only necessary to compute the ratio of summed foil activities in each of the two foil arrays, use this ratio to determine the effective neutron energy from Fig. 8, and then apply this energy to the curves

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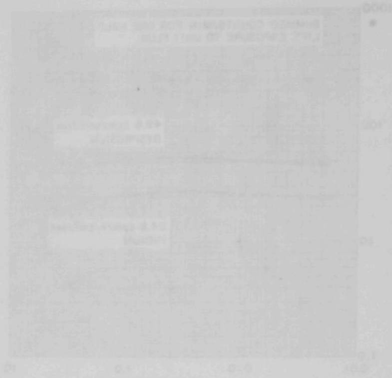

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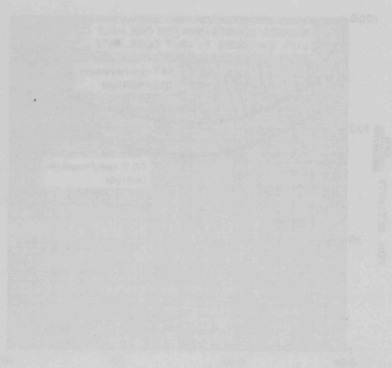

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To determine fluence and dose equivalent accurately, it is only necessary to compute the ratio of summed foil activities in each of the two foil arrays, use this ratio to determine the effective neutron energy from Fig. 8, and then apply this energy to the curves in Figs. 5 and 6 to determine the sensitivity figures to be utilized with each array. A corrected fluence and dose equivalent then may be computed from the original foil-activity data.

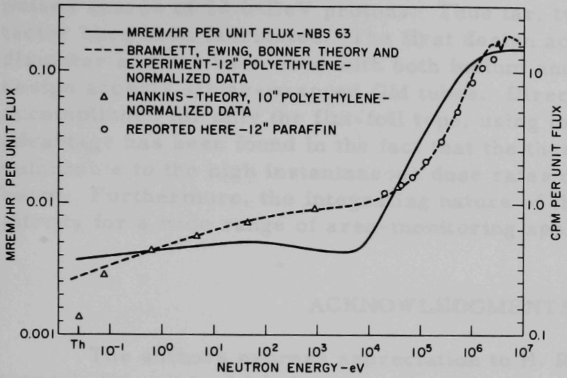

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Fig. 7

Comparison of Response Characteristics of Three Spherical Neutron Detectors (in central dosimetric region) with Accepted RBE Dose Rate Function

The accuracy that can be achieved depends on a number of factors, among them:

1. the accuracy of the basic monoenergetic neutron calibration;

2. the accuracy of the determination of foil activity;

3. the nature of the neutron-energy distribution.

In principle, the errors due to the first two factors can be reduced to negligible proportions. Our experience indicates that an accuracy of 10 percent in determination of fluence and dose equivalent can be achieved for monoenergetic beams at typical "tolerance" levels, provided the basic calibration curve is deemed to be exact. If neutrons are not monoenergetic, as is usually the case in practical measurements, there will be an unavoidable error caused by a weighting of the actual neutron spectrum by the response of the instrument before the average is struck. However, having determined the detector response to monoenergetic neutrons, it is possible to prepare response curves for application to "flat," 1/E, Gaussian, and other spectra.

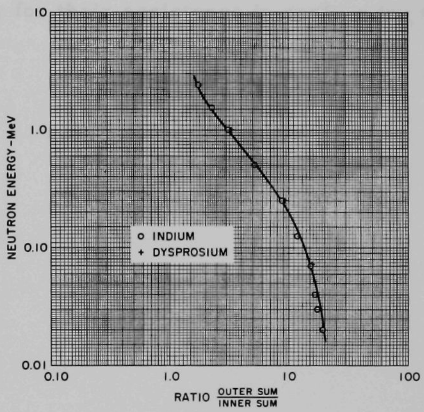

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Fig. 8. Ratio of Outer to Inner Foil-array Activities. The derived neutron energy is the true value for a monoenergetic source or an effective value for other types of spectra.

APPLICATION

The first and current application of the instrument is the monitoring of radiation in the environs of the Argonne Zero Gradient Synchrotron, a pulsed source of 12.6-BeV protons. Thus far, two foil versions of the detector have been fabricated. The first design accepts flat foils up to 2 in. in diameter and has been used with both indium and dysprosium. The second design accepts silver-wrapped GM tubes. Direct calibration has so far been accomplished for only the flat-foil type, using indium and dysprosium. Great advantage has been found in the fact that the thermal activation foils are invulnerable to the high instantaneous dose rates of the pulsed accelerator beam. Furthermore, the integrating nature of the foils affords adequate sensitivity for a wide range of area-monitoring applications.

ACKNOWLEDGMENTS

The authors express appreciation to H. R. Sebastian for his assistance in the work of fabricating and calibrating the detector. They also thank various members of the Instrument Shop of Argonne's Industrial Hygiene and Safety Division and to the operating staff of the Van de Graaff accelerator in the Physics Division of the Laboratory for their assistance in performing the calibration experiment.

REFERENCES

1. Oleson, F. B., Neutron Monitoring with Indium Foils, BNL-351 (July 1955).

2. Wallace, R., Moyer, B. J., Patterson, H. W., Smith, A. R., and Stephens, L. D., The Dosimetry of High Energy Neutrons Produced by 6.2 BeV Protons Accelerated in the Bevatron, UCRL-9214 (May 1960).

3. Smith, A. R., A Cobalt Neutron-flux Integrator, Health Physics 7, 40-47 (1961).

4. Mandl, Mrs. M. E., A Method of Measuring the Average Energy of a Neutron Spectrum in the Range 0.3 to 3.0 MeV, AERE-T/R-1008 (Aug. 1952).

5. Fraki, R., Leimdorfer, M., and Mulmskog, S., The Energy Variation of the Sensitivity of a Polyethylene Moderated BF_3 Proportional Counter, Nuclear Instruments and Methods 23, 341-348 (1963).

6. Acto, H., Jr., and Churchill, B. W., Neutron Depth Dose from (α,n) and (γ,n) Sources in a Tissue-equivalent Phantom, UCRL-10267 (March 1963).

7. Bramblett, R. L., Ewing, R. I., and Bonner, T. W., A New Type of Neutron Spectrometer, Nuclear Instruments and Methods 9, 1-12 (1960).

8. Hankins, D. E., A Neutron Monitoring Instrument Having a Response Proportional to the Dose Rate from Thermal to 7.0 MeV, LA-2717 (Aug 1962).

9. DePangher, J., A Reproducible Precision Polyethylene Long Counter for Measuring Fast Neutron Flux, HW-SA-2140 (April 1961).